

REPORT NO. 1195
MARCH 1963

THE DOPLOC DARK SATELLITE TRACKING SYSTEM

A. L. G. deBey
V. W. Richard

PROPERTY OF U.S. ARMY
STINFO BRANCH
BRL, APG, MD. 21005

COUNTED IN

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BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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ALGdeBey/VWRichard/cet
Aberdeen Proving Ground, Md.
March 1963

THE DOPLOC DARK SATELLITE TRACKING SYSTEM

ABSTRACT

The DOPLOC "dark" satellite tracking system is described and tracking results are presented. DOPLOC is a radio reflection Doppler tracking system deriving its name from the Doppler frequency phase-locked tracking filter technique used. Dark, i.e. non-radiating, satellites are illuminated by a ground-based transmitter and signals reflected from illuminated satellites are received at one or more ground-based receiving sites.

A method has been developed for the determination of a complete set of orbital parameters from Doppler data recorded in the course of a single pass of a satellite.

Numerous orbital solutions have been obtained with Doppler data from a single receiver recorded during a single pass of a satellite. Computing times of 2 to 4 minutes are required with the BRLESC computer.

The DOPLOC tracking method has general application to the tracking of projectiles, rockets, guided missiles and space vehicles.

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INTRODUCTION

The DOPLOC (Doppler Phase Lock) dark satellite tracking system is a radio reflection Doppler system deriving its name from the Doppler frequency phase-locked tracking filter technique used. Dark, i.e. non-radiating, satellites are illuminated by a ground-based transmitter and signals reflected from illuminated satellites are received at one or more ground-based receiving sites.

The frequency of the transmitted signal is compared with the frequency of the signal received via reflection from the satellite and the difference, or Doppler frequency, constitutes the basic data from which orbital parameters are determined. A method has been developed for the determination of a complete set of orbital parameters from Doppler data recorded in the course of a single pass of a satellite. The ability of the DOPLOC system to provide complete orbital parameters, using only a few minutes of Doppler observations obtained from a dark satellite during the course of a single pass, provides a solution to a number of difficult and important space vehicle tracking problems. For example, it is desirable to know the orbital parameters as quickly as possible after launching a satellite. The orbital parameters of a newly launched satellite can be computed from DOPLOC data within minutes after the beginning of its free flight. Again, after attempting to deflect or steer a satellite into a different orbit, it is desirable to know the new orbital parameters within minutes after giving the steering command. It is also desirable to keep track of satellites after their transmitters have ceased operating or in cases where the transmitting frequencies are not suitable for tracking or are unknown.

Considerable impetus was given to the development of reflection Doppler techniques and instrumentation when, under a directive issued by the Advanced Research Projects Agency (ARPA) in June 1958, a DOPLOC system was installed as part of a national passive satellite detection fence across the southern portion of the United States. This directive placed the responsibility on the Ballistic Research Laboratories to develop a long range passive Doppler tracking system, to construct, instrument and supervise the operation of tracking stations, to analyze received signals, and to produce orbital parameters of non-radiating satellites passing over a specified area of the continental United States. In response to the ARPA directive, the DOPLOC dark satellite tracking system was developed.

A three-station interim DOPLOC complex was installed in the center portion of the Satellite Detection Fence consisting of an illuminator transmitter at Fort Sill, Oklahoma, and receiving stations at Forrest City, Arkansas and White Sands Missile Range, New Mexico (Fig. 1). Although this complex ceased operation in June 1961, the equipment, Doppler tracking techniques, output data and results described in this paper are illustrative of the basic DOPLOC system.

DOPLOC SYSTEM DESCRIPTION

Transmitting Station

A 50 kw, 108 mc, continuous wave illuminator transmitter was used at the Fort Sill site, which was midway between the two receiving sites it served. Three transmitting antennas were provided, each with a fan beam shaped radiation pattern 8° by 76° and 16 db gain (Fig. 2). The fan beam pattern of the center antenna was vertically directed with its broad dimension oriented east-west. The beams of the other two antennas were directed 20° above the northern and southern horizon, respectively, with their broad pattern dimension horizontal. The transmitter could be quickly switched to any one of the three antennas.

Receiving Stations

Three antennas, each with a fan beam pattern $8^\circ \times 76^\circ$, were used at each receiving station. These antennas were oriented for maximum beam pattern volume overlap with the transmitting antennas. The central axes of the receiving and transmitting antennas intersected at about 900 miles range. In this manner, the antennas were oriented to detect the approach of a satellite as it came over the horizon, intercept it again overhead, and again as it receded toward the horizon (Fig. 3). The successive passage of a satellite through the three antenna beams provided three segments of the Doppler "S" curve as shown in Fig. 3.

Doppler Data

Doppler frequency is defined to be the frequency obtained by heterodyning a locally generated signal against the signal received from the satellite, followed by a correction for the frequency bias introduced as a result of the difference between the frequency of the local oscillator and that of the

transmitter. If the Doppler frequency, as defined, is plotted as a function of time for a satellite in orbit, one obtains an "S" curve of the form shown in Fig. 4(a). The asymmetry of the curve is typical for a tracking system with a ground-based transmitter and receiver separated by an appreciable distance. This asymmetry contributes greatly to the unambiguous determination of the orbital parameters from single pass data. Only for a satellite whose orbital plane bisects the base line will the Doppler data produce a symmetrical "S" curve. Fig. 4(a) illustrates an analog plot of the Doppler frequency received from tracking a satellite-borne transmitter. With a ground-based transmitter it is not economically feasible to illuminate the entire volume of space under surveillance; therefore, it is necessary to limit the number of observations to minimize the cost and complexity of the transmitter and antennas. The interim system installed in the Fence provided three sections of the "S" curve as shown in Fig. 4(b). Studies made subsequent to the interim Fence operation have shown that an optimum system should use a scanning fan beam antenna, providing a number of discrete observations at regular intervals, as shown in Fig. 4(c). Data in any of these forms may be used as input for the orbital parameter computing procedure, but, in order to handle the Doppler data rapidly and accurately, the Doppler frequency must be automatically counted and digitized at the receiving sites. Automatic, real-time counting of the Doppler Frequency requires a signal of high quality, i.e., with very low noise content. High quality Doppler data, which are essentially noise free, are provided in the DOPLOC system by use of a very narrow bandwidth, phase-locked tracking filter following the receiver. The tracking filter must initially acquire the signal and be adjusted precisely in frequency (i.e. phase-locked) to the Doppler signal before it can function as a noise clean-up device.

Automatic Search and Lock-On

One of the most significant developments of the DOPLOC system was a signal search and lock-on device which automatically placed the tracking filter on any signal occurring within the search frequency range of the equipment. The signals received via reflection from a satellite were very weak, ranging from 10^{-16} to 10^{-19} watts, which put them as much as 30 db (1000 times in power) below the noise at the receiver output. The receiver had a bandwidth of 16 kc to accommodate the range of Doppler frequencies which extended from

2 to 14 kc. The signals were of short duration, averaging about 8 seconds in the center beam. Thus, short duration, weak, noisy signals made it necessary to use a very sensitive, fast search, automatic lock-on (ALO) system. The ALO system developed used a comb filter frequency search unit. To meet the requirements of minimum search time, ten filters of 10 cps bandwidth were placed in the desired audio frequency band and the signal was fed to all of the filters. The ten filters were spaced 100 cps apart to cover a 1 kc band. These ten filters were switched twelve times to cover the full 12 kc band. The rate of switching determined the time available to find a signal as well as the total sweep time. Three switching rates were used, 2.5, 5 and 10 cps. When the 10 cps rate was used, the time for each 1 kc band was 0.1 second and 1.2 seconds for the entire Doppler frequency band. If a signal was present in the noise in the frequency range from 2 to 14 kc, possessing sufficient amplitude and was within the bandwidth of one of the fixed filters, it activated that filter. The filter, upon receiving a signal, closed its control relay which put an oscillator frequency equal to that of the filter into a circuit termed the "set frequency" control. This circuit compared the fixed filter oscillator frequency with the tracking filter oscillator frequency and generated an error voltage which was applied to the tracking filter to produce a phase-lock between the oscillators. The tracking filter was then switched to the track position where the tracking filter loop was closed and a phase-lock was obtained on the true input signal. This search and lock-on sequence required a maximum of 1.2 seconds, which was adequate for the three antenna system. A newer automatic search system using a bank of 1200 transistorized filters, has been developed recently to permit scanning the 2 to 14 kc range in 0.1 second. The need for this faster time response arose in connection with the proposed scanning DOPLOC system, where a narrow beamwidth scanning antenna would repeatedly sweep past a satellite, resulting in signal durations of about 0.1 second.

Tracking Filter

The tracking filter provides special noise filtering characteristics, making possible the successful reception of the extremely low energy signals returned from satellites at long ranges. Large improvements in the signal-to-noise ratio of noisy received signals are realized by extreme reduction of the

system bandwidth through the use of the tracking filter. Bandwidths adjustable from 1 to 100 cps are available, with 10 cps normally used. The tracking filter is capable of phase-locked operation when the input signal is a maximum of 38 decibels below the noise, (i.e., a noise-to-signal ratio of 6300 when the receiver bandwidth is 16 kc and the filter bandwidth is 1 cps). The tracking filter is an electronic bandpass filter whose center frequency automatically tracks the frequency of the input signal. The filtering action is obtained by use of a frequency-controlled oscillator that is correlated (phase-locked) with the input signal. The basic block diagram of the tracking servo loop is shown in Fig. 5. Tracking is accomplished with an electronic servo system designed to make the frequency-controlled oscillator follow the frequency and phase of the input signal. This electronic servo system has been designed to yield essentially zero tracking error for a constant rate of change of input frequency. An inherent feature of this third-order servo control design is an effective acceleration memory which provides tracking through signal dropouts. Experience with signal reception from satellites has proved the necessity for this memory feature, since the received signal amplitude may vary widely and rapidly. The filter works through null periods very effectively without losing lock. In addition, this memory provides effective tracking of the desired Doppler signal in the presence of interfering signals or when several satellites are within receiving range simultaneously.

The signal-to-noise power improvement furnished by the tracking filter is equal to the ratio of the input source noise bandwidth to the filter bandwidth. The internal noise generated by the filter is negligible at all bandwidths. The relation between input and output signal-to-noise is shown in Fig. 6, where the threshold sensitivity for a receiver with a 1 cps bandwidth and 3 db noise figure is shown to be 2×10^{-20} watts (-197 dbw, or 0.001 microvolts across 50 ohms).

An experimental study has been made of the relation between signal-to-noise ratio and the uncertainty or random error in measuring the frequency of a Doppler signal. The test results showing rms frequency error as a function of signal-to-noise ratio and tracking filter bandwidth are shown in Fig. 7. An integration time or counting interval of one second was used for these measurements. As a typical example, a signal 24 db down in the noise can be read to an accuracy of 0.08 cps when a 10 cps filter bandwidth is used.

Since the key to successful determination of orbits from a minimum number of observations lies in obtaining data with small values of random and systematic error, the high quality data output of the DOPLOC receiving system and tracking filter has been an important feature.

Data Handling

The basic Doppler information, available at the output of the tracking filter, was a constant amplitude, varying frequency sine wave. Recording was accomplished in both analog and digital form, utilizing magnetic tape recorders, strip-chart recorders, digital printers and teletype tape punches. To permit rapid data handling and real time transmission to the computer, it was necessary to digitize and encode the Doppler data at the receiving stations. The digitized Doppler data were transmitted via teletype to the Ballistic Research Laboratories where the received data, recorded on punched paper tape, were in binary format suitable for feeding directly into the BRL ORDVAC computer used for the calculation of orbital parameters.

Magnetic tape recordings were also made of the raw, unfiltered data at the output of the receiver, which served as back-up data should a failure occur in the tracking filter-digitizing system during a satellite pass. This is a unique advantage of the audio frequency tracking filter used in the DOPLOC system in contrast to systems that use phase-locked filters in the radio frequency portion of the system. The latter systems cannot record the unfiltered signals and, consequently, have no back-up data in the event of a filter malfunction.

TRACKING RESULTS

Doppler Data

Examples of recorded data are shown in Figs. 8 and 9. Fig. 8 is a dual channel, strip-chart record of data obtained on Revolution 140 of satellite 1960 Delta (Discoverer XI). The upper record indicates frequency as a function of time, showing the three segments of the "S" curve. These segments correspond to the times of passage of the satellite through the three antenna beams. The step wave forms show the functioning of the automatic search and lock-on system. The lower channel indicates the received signal strength. Fig. 9 shows two

types of Doppler data output records. The first is the punched paper type in binary code on standard five-level teletype tape. The first punched data block contains Universal Time at the beginning of the run. Subsequent data blocks, recorded once per second, contain the Doppler data to the nearest 0.1 cycle per second. The second type of recording is the printed paper tape in Arabic numerals. Two examples are shown, one of Doppler frequency and the other the inverse of the frequency, or Doppler period. Each line contains Universal Time and the Doppler data at print-out time. The Doppler period print-out gives an order of magnitude higher resolution of Doppler recording than the frequency print-out.

Orbit Computation Procedure

The method of orbit solution consists of a curve-fitting procedure, in which a compatible set of approximations for the orbital parameters are improved by successive differential corrections. The approximations are obtained from a least-squares treatment of an over-determined system of equations of condition. The imposed limitation of single pass detection permits several assumptions which considerably simplify the computing procedure. Among these is the assumption that the Earth may be treated dynamically as a sphere while geometrically regarding it as an ellipsoid. In addition, it is assumed that no serious loss in accuracy will result if drag is neglected as a dynamic force. With these assumptions, it is apparent that the satellite may be regarded as moving in a Keplerian orbit. Since the system operates at the relatively high frequency of 103 mc, it is feasible to neglect both atmospheric and ionospheric refraction effects. The analog data are used to determine initial position and velocity components from which are computed orbital parameters, position and velocity components versus time and Doppler frequency versus time. The latter data are compared to the observed Doppler data in a mathematical comparison routine. Differential corrections are derived and used to correct the initial point estimates. This iterative process is repeated until the corrections fall below predetermined lower limits after which the process is stopped and the final orbital parameters are printed out by the computer.

Convergence of the computation rests primarily upon the adequacy of the initial approximations for position and velocity. It has been established that, for a system consisting of a single receiver and an earth-bound transmitter at opposite ends of a 400 mile base line, convergence is assured when the error in each coordinate of the initial estimate is not in excess of 50 to 75 miles and the velocity components are correct to within (1/2 to) 1 mile per second. However, if single pass measurements are available from two or more receivers, the system geometry is greatly strengthened. Convergence can then be expected when the initial approximations are within (50 to) 100 miles of the correct value in each coordinate and (1 to) 2 miles per second in each velocity component. Several successful methods have been developed for computing sufficiently accurate initial approximations to position and velocity to assure convergence of the primary computation. Fig. 10 illustrates a graphical method for determining initial position estimates from the analog data. The measured values of Doppler frequency and rate of change of frequency at the time of passage through the midpoint of the vertical beam are entered on the graph. Associated values of satellite altitude and distance east of the transmitter site can be read. The north-south position of the satellite is on the great circle path connecting the transmitter and receiver since the data are taken at the time the satellite is in the center of the vertical antenna beam. Velocity components are determined consistent with the assumption of circular motion, the height, which is determined graphically, and the assumed inclination. In addition to the graphical solution, a digital method has been developed which is suitable for machine computation. This method established an approximate orbit to provide initial approximations for the more sophisticated primary computation which in turn yields a refined orbit determination.

Results of Orbital Computation

Numerous convergent solutions have been obtained with actual field data from a single receiver. Orbital parameters computed from DOPLOC data obtained for 1960 Delta (Discoverer XI) are shown in Fig. 11. Measurements were recorded for 14 seconds in the north antenna beam, 7 seconds in the center beam, and 8 seconds in the south beam, with two gaps of about 45 seconds each in the data. Thus, observations were recorded for a total of 29 seconds

within a time interval of two minutes. Using the graphical method described above to obtain initial approximations, convergence was achieved in three iterations, on the first pass through the computing machine. It will be noted, in the comparison of DOPLOC and Space Track (National Space Surveillance Control Center, Bedford, Massachusetts) results, that there is good agreement in the semi-major axis, eccentricity, inclination and right ascension of the ascending node. This is characteristic of the single pass solution when the eccentricity is small and the computational input is limited to Doppler frequency. Since the orbit is very close to being circular, the mean anomaly at epoch and argument of perigee are difficult for either the DOPLOC System or Space Track to determine accurately. When limited to single pass, single-receiver observations, the DOPLOC system provides an excellent determination of the orientation of the orbital plane, a good determination of the shape of the orbit, and a fair-to-poor determination of the orientation of the ellipse within the plane.

As an example of the accuracy of DOPLOC observations and the strength of the orbital computation method, a solution was determined using only seven frequency observations during the passage of 1958 Delta (Sputnik III). The observations were selected to serve as an example of the type of reduction required for the proposed DOPLOC scanning beam antenna system. The results, presented in Fig. 12, show very good agreement with the published orbit. This example shows that the method is quite feasible for use with periodic, discrete measurements of Doppler frequency. Of course, the proposed system would normally yield several more observations than were available in this example.

CONCLUSION

It is noteworthy that numerous solutions have been obtained with field data from a single DOPLOC receiver recorded during a single pass of a satellite. Further, these measurements have been confined to three short periods of observation within a two to three minute interval. Additional receivers spread over greater distances would, of course, considerably enhance the accuracy of the results. For example, a system with two receivers and a ground transmitter would reduce error propagation in the computations to approximately one-tenth of that to be expected from a system with a single receiver. Removing the restriction of single pass determination would further enhance the accuracy of the results.

Computing times have been found to be reasonable. Convergent solutions have required 20 to 40 minutes on the BRL ORDVAC which requires the coding to include floating decimal sub-routines. More modern machines, such as the BRLESC now in operation at the Ballistic Research Laboratories, could perform the same computation in 2 to 4 minutes. Hence, it is realistic to state that the system has the potential capability of orbit determination within five minutes after observation time. In addition, the DOPLOC tracking methods has general application and, therefore, need not be confined to satellites in Keplerian orbits. Other applications would be the tracking of projectiles, rockets, guided missiles and space vehicles for the determination of acceleration and velocity components and trajectory parameters.

A. L. G. DEBEY

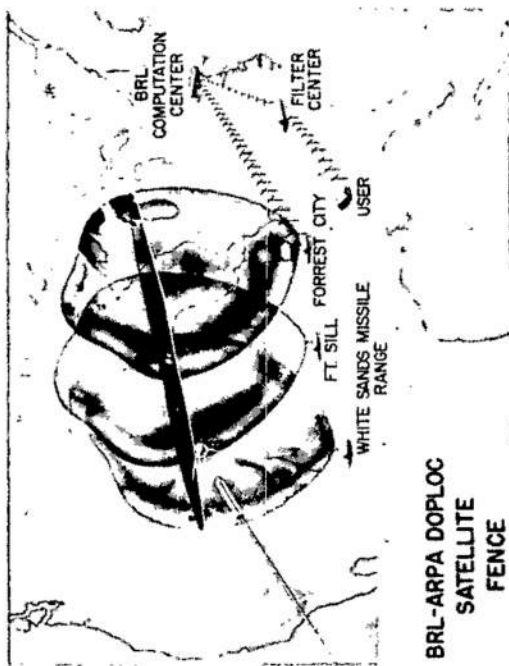
V. W. RICHARD

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6. Hodge, A. H. Final Technical Summary Report Period 20 June 1958-30 June 1961 BRL-ARPA DOPLOC Satellite Detection Complex BRL Report No. 1136, July 1961.



FIG. 2. TRANSMITTING ANTENNAS



BRL-ARPA DOPLOC
SATELLITE
FENCE

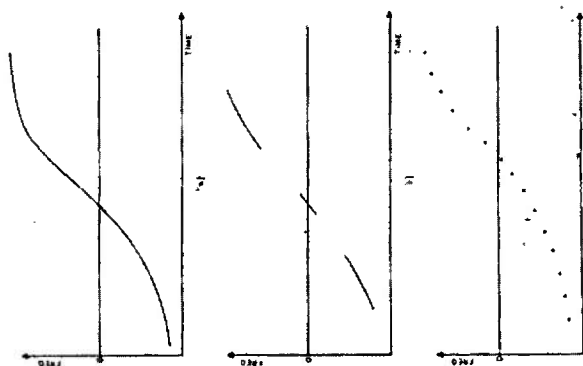
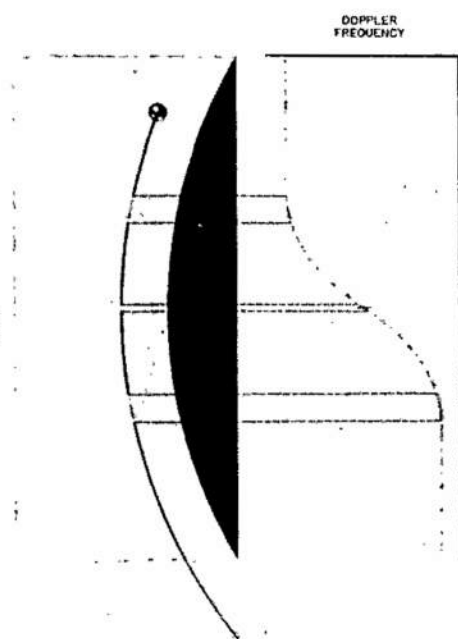
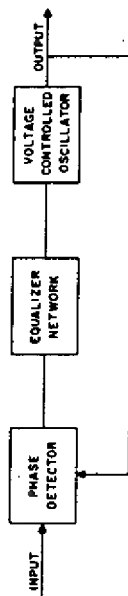


FIG. 4. DOPPLER FREQUENCY - TIME CURVES



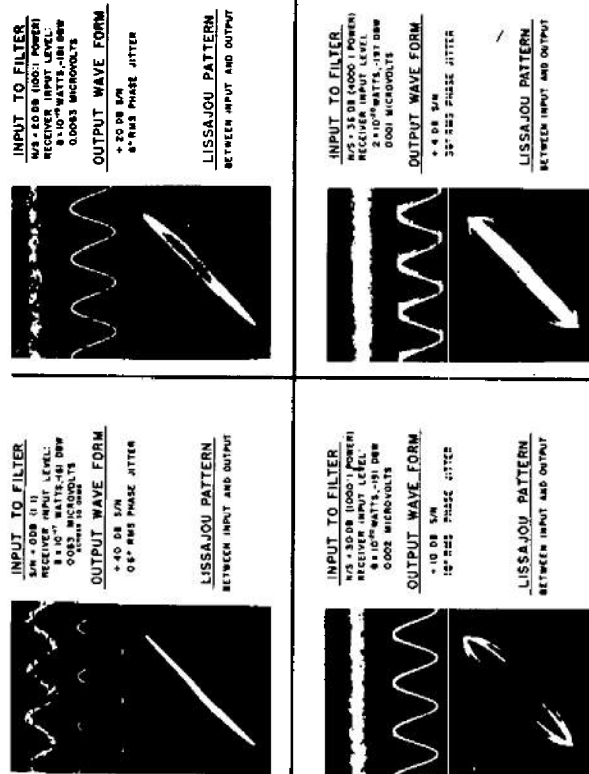
BASIC INTERIM DOPLOC SYSTEM

FIG. 3



BASIC TRACKING FILTER SYSTEM

FIG. 5



INPUT & OUTPUT WAVEFORMS VS. NOISE TO SIGNAL RATIO FOR 1 CPS BANDWIDTH

FIG. 6

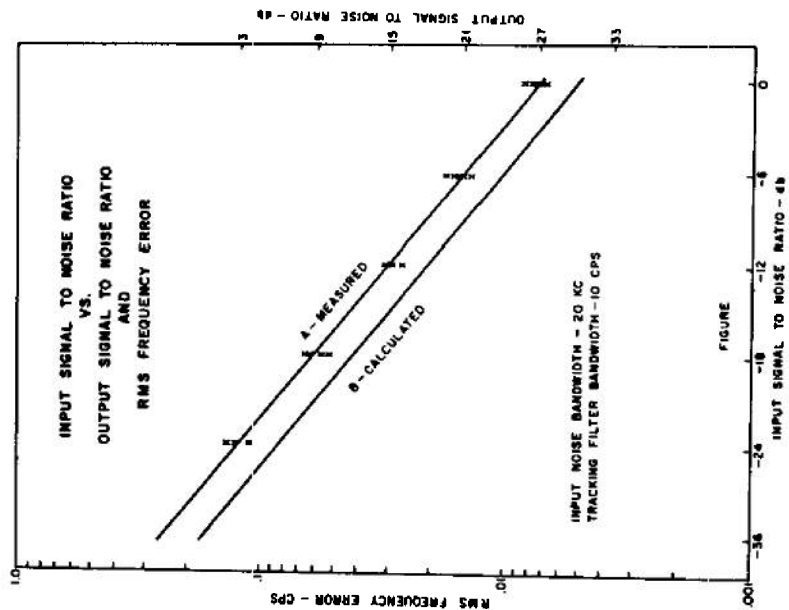
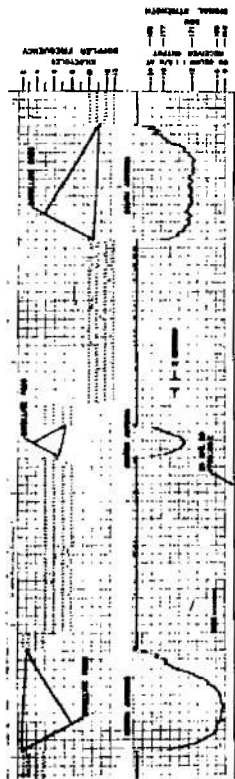
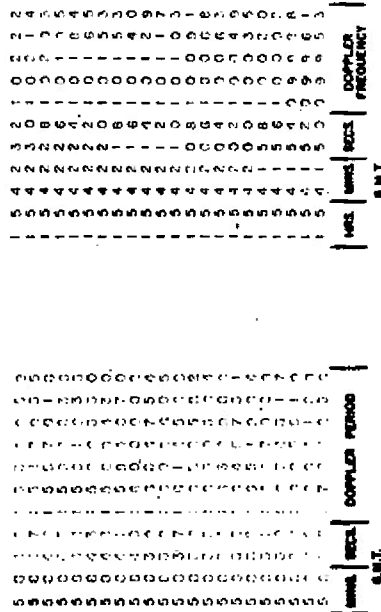
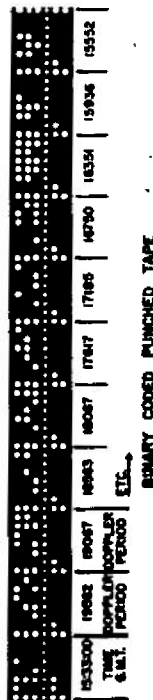


FIG. 7

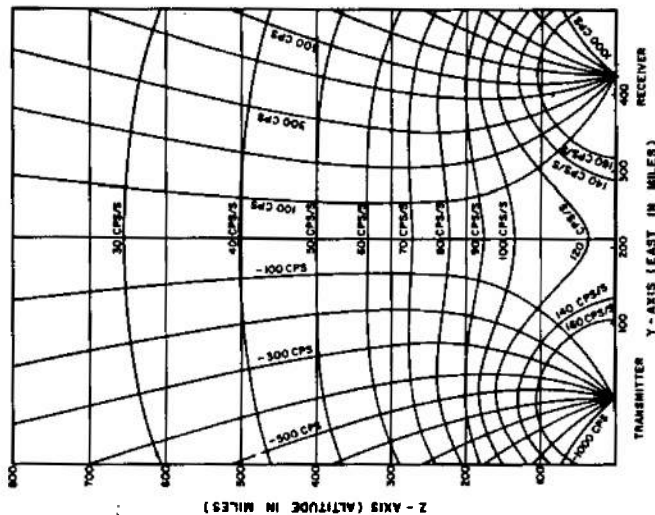


DOPPLER RECORD OF 80 DELTA, REV. 140, FORREST CITY, ARKANSAS
17:28:06Z, ALTITUDE 116 MILES, 320 MILES EAST FORT SILL
FIG. 8



TYPICAL DOPLOC DATA OUTPUT

FIG. 9



DOPLOC FREQUENCY AND RATE OF CHANGE OF FREQUENCY AS A FUNCTION OF POSITION IN THE YZ-PLANE (FOR 80° INCLINATION)

FIG. 10

TYPICAL SINGLE PASS DOPPLER ORBIT SOLUTION
 (BY ARMY-DOPLOC SATELLITE TRACKING SYSTEM)
 REVOLUTION NO. 30 OF 1960 DELTA (DISCOVERER XII)

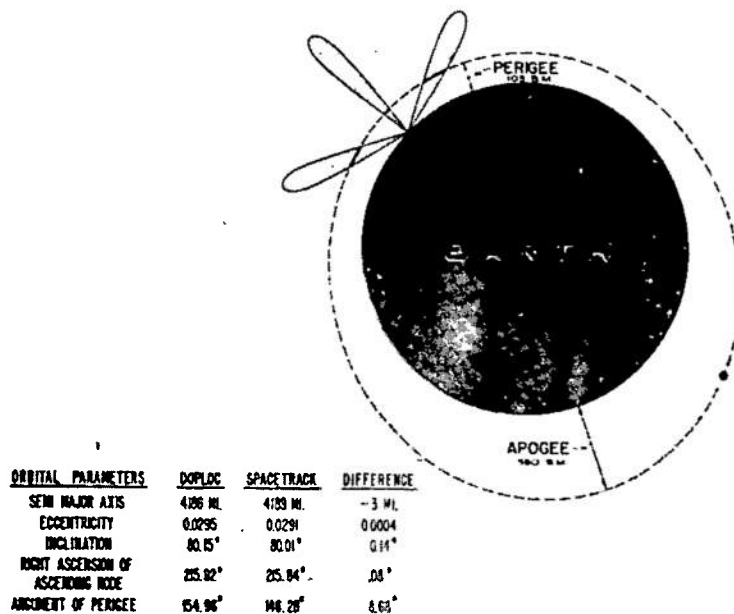


FIG. 11

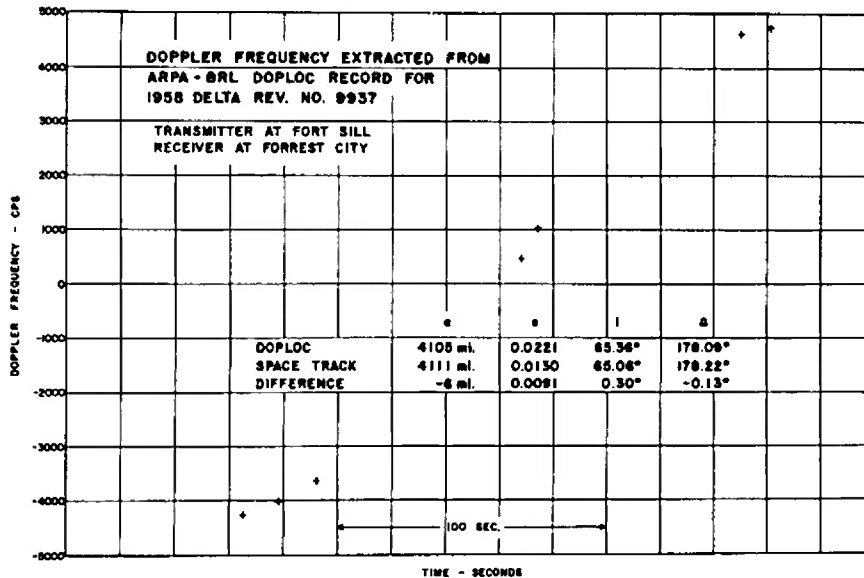


FIG. 12

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 UNCLASSIFIED Report

Satellites - Detection
 Radar tracking -
 Satellites
 Doppler tracking systems -
 Design

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